This document was prepared in conjunction with work accomplished under Contract No.
DE-AC09-76SR00001 with the U.S. Department of Energy.

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SAVANNAH RIVER LABORATORY

DPST-82-331

ACC. NO. 147312

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February 22, 1982

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THEORETICAL BASIS FOR THE DESIGN OF A DWPF EVACUATED CANISTER

Introduction and Summary

The use of an evacuated canister for draining glass from a melter was first suggested to SRL by the Europeans during a recent technical exchange. The technique was successfully demonstrated on the Small Cylindrical Melter (SCM) at TNX[1] but later failed on three successive occasions when attempted on the 1941 melter due to premature freezing of the glass in the suction pipe before flow into the canister was established.

The simplicity of this technique makes it very attractive for draining a DWPF melter. However, the technique must be demonstrated to be reliable before usage in a canyon environment can be endorsed.

Conservation laws have been used to develop equations for predicting the performance of evacuated canisters, and are presented here. Specific design recommendations are made to ensure satisfactory performance of the canisters in future tests.

1. Basic Conservation Laws

An evacuated canister consists of three main parts - a fusible plug, a suction pipe, and a suitable canister. In order to prepare the canister for usage, the fusible plug (usually aluminum) is screwed into one end of the suction pipe and the entire canister and pipe evacuated to a high vacuum. The evacuated canister and pipe are then positioned such that the fusible plug is submerged in the glass pool which is to be drained (Figure 1). When the plug melts, glass then rises up the suction pipe and is discharged into the evacuated canister. If the glass flow can be kept isothermal (or nearly so) such that the glass does not cool and solidify, it is possible to drain the glass from the melt pool into the canister.

Now consider a metal pipe submerged in a molten glass pool as shown in Figure 2. The bottom of the pipe is initially sealed with an aluminum plug (melting point ∿615°C) and the inside of the pipe is assumed to have been previously evacuated to a pressure of approximately P = 0 psia. The melter plenum is assumed to be at P_{atm} = 14.7 psia. At time t = 0, the aluminum plug melts and molten glass begins to flow up into the pipe.

Conservation of mass requires that

$$\rho \pi R_i^2 \frac{dh}{dt} = \rho \pi R_i^2 v \qquad (1\text{-}1)$$

where

- ρ = glass density [lb_m/ft^3],
- R_i = inside radius of the pipe [ft],
- h = height of the glass inside the pipe [ft],
- t = time [secs],
- v = glass velocity in the z-direction as it enters the pipe [ft/sec].

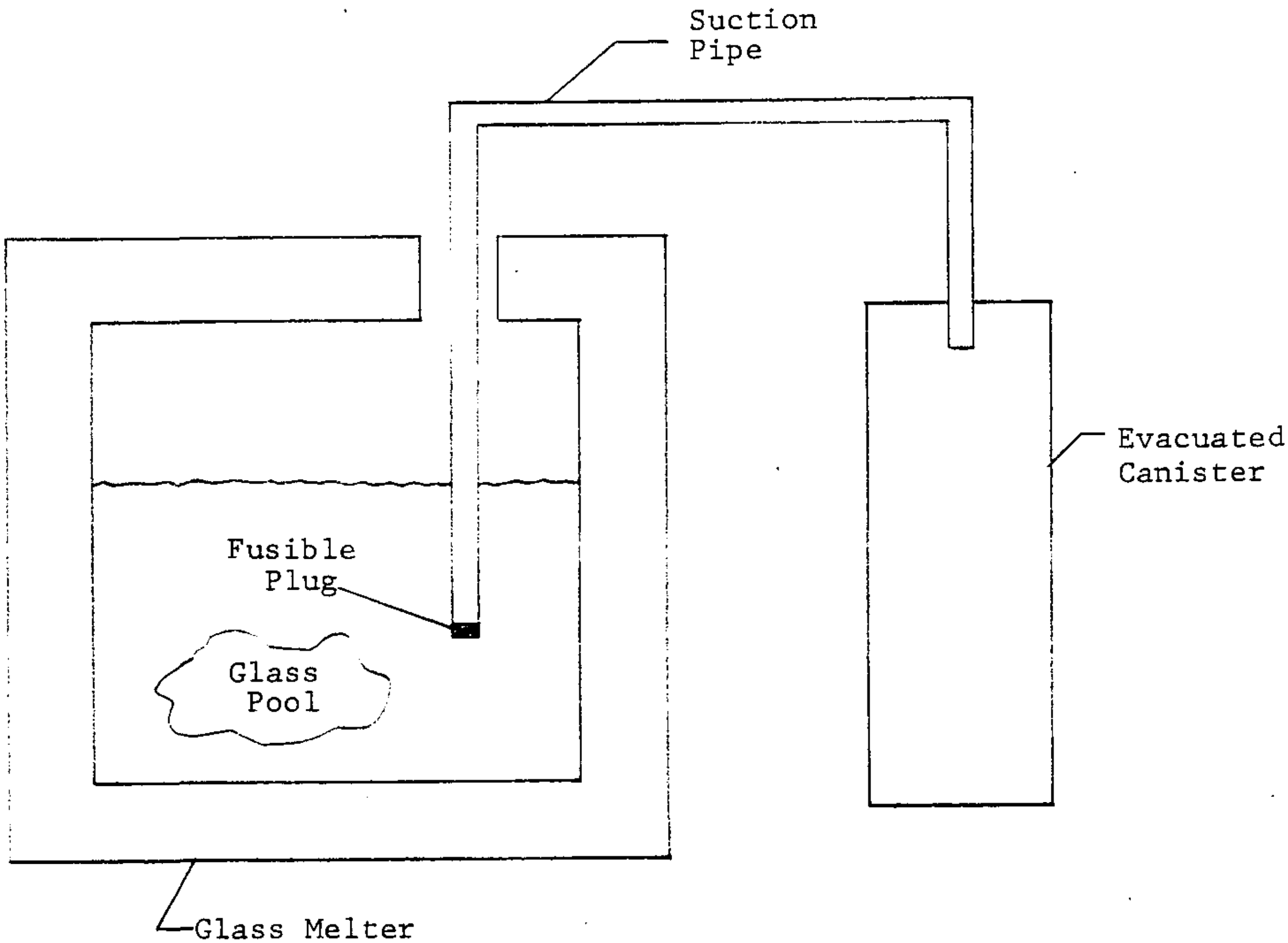

FIGURE 1 - BASIC CONCEPT OF AN EVACUATED CANISTER

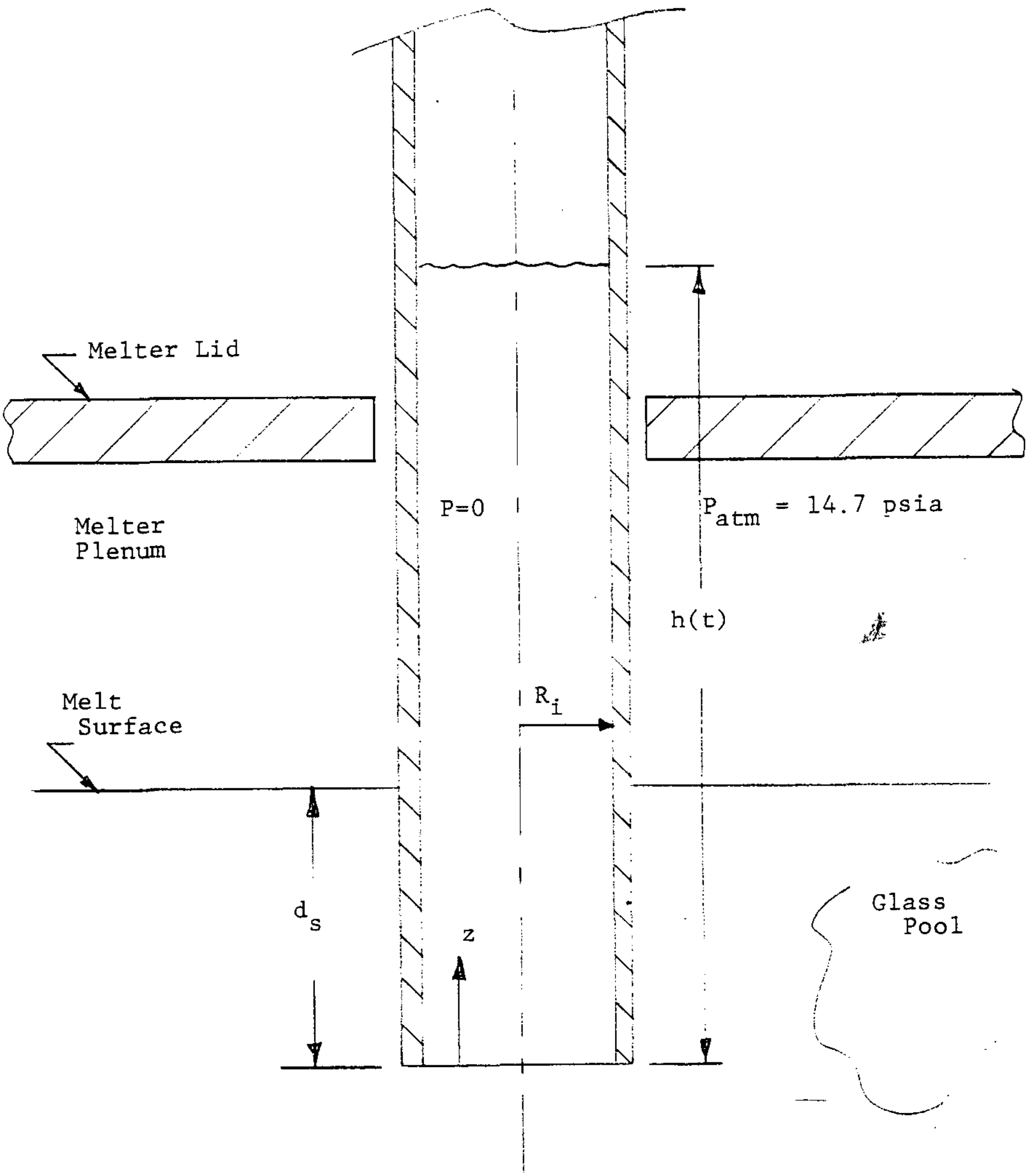

FIGURE 2 - EVACUATED PIPE SUBMERGED IN A GLASS POOL

For incompressible flow*, (1-1) reduces to

$$\frac{dh}{dt} = v \tag{1-2}$$

A momentum balance on the glass flowing up the pipe requires that

Change in momentum of glass in pipe = Upward forces at bottom of pipe
- Frictional forces
- Gravitational forces

$$\rho\pi R_i{}^2\frac{d(hv)}{dt} = 144\ P_{atm}\pi R_i{}^2 g_o + \rho\pi R_i{}^2 d_s g - F_{fric} - \rho\pi R_i{}^2 hg \tag{1-3}$$

where

g_o = standard gravitational constant
= 32.14 lb_m-ft/lb_f-sec², ,

d_s = submerged depth of the pipe beneath the surface of the glass pool [ft],

F_{fric} = frictional force [lb_m - ft/sec²],

g = local gravity [ft/sec²].

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* Requires the assumption that glass density is constant or nearly so.

For laminar flow in a pipe the frictional force is given by[2]

$$F_{fric} = \frac{16\pi\rho R_i h v^2}{N_{Re}} \tag{1-4}$$

where N_{Re} is the Reynolds number. The Reynolds number is defined as

$$N_{Re} = \frac{2\rho v R_i}{\mu} \tag{1-5}$$

where

μ = glass viscosity* at temperature T [lb_m/ft-sec].

Using (1-5) in (1-4) reduces the frictional force to

$$\boxed{F_{fric} = 8\pi\mu h v} \tag{1-6}$$

Equations (1-2) and (1-3) represent two, coupled, non-linear differential equations in h(t) and v(t). Furthermore, since the glass viscosity is a function of temperature these two equations will couple to a third differential equation for conservation of energy unless the glass flow is kept essentially isothermal. Isothermal flow will be assumed valid at present, and its impact on canister design subsequently examined. The non-linearity of (1-2) and (1-3) will be treated by first developing an approximate solution for initiation of flow up the suction pipe for small values of t. The steady state solutions of (1-2) and (1-3) will then be developed for large values of t.

* 1 Poise = 0.06722 lb_m/ft-sec.

2. Initiating Isothermal Flow

Referring to (1-3) define

$$C_1 = \rho\pi R_i^2 \quad (2\text{-}1)$$

$$C_2 = \pi R_i^2 \; (144P_{atm}g_o + \rho d_s g) \quad (2\text{-}2)$$

$$C_3 = 8\pi\mu(T_o) \quad (2\text{-}3)$$

$$C_4 = \rho\pi R_i^2 g \quad (2\text{-}4)$$

where

$\mu(T_o)$ = glass viscosity at temperature T_o [lb_m/ft-sec],

T_o = glass temperature entering the pipe [°R].

Equation (1-3) reduces to

$$C_1\frac{d(hv)}{dt} = C_2 - C_3hv - C_4h \quad (2\text{-}5)$$

Multiplying (2-5) by dt and using (1-2) gives

$$C_1\int_0^{hv} d(hv) = C_2\int_0^t dt - C_3\int_0^h hdh - C_4\int_0^t hdt \quad . \quad (2\text{-}6)$$

Integrating (2-6) gives

$$C_1hv = C_2t - 0.5C_3h^2 - C_4\int_0^t hdt \quad . \quad (2\text{-}7)$$

Define the average value of h at time t as

$$\bar{h}(t) = \frac{\int_0^t h\,dt}{\int_0^t dt} \quad . \tag{2-8}$$

Equation (2-7) then becomes

$$C_1 hv = C_2 t - 0.5 C_3 h^2 - C_4 \bar{h} t \tag{2-9}$$

If one makes the approximation that for small values of t

$$\bar{h} \simeq \frac{h(t^*)}{2} \quad , \quad t^* \neq t \tag{2-10}$$

where t^* is arbitrarily close to t, then $\bar{h}$ becomes a function of t^* only. Also

$$h^2 \simeq 2\bar{h}(t^*)h(t) \quad . \tag{2-11}$$

Using (1-2) and (2-9) gives

$$C_1 h \frac{dh}{dt} \simeq C_2 t - C_3 \bar{h}(t^*) h - C_4 \bar{h}(t^*) t \quad . \tag{2-12}$$

Multiplying (2-12) through by dt and integrating gives

$$C_1 h^2 \simeq C_2 t^2 - 2C_3 \bar{h}(t^*) \bar{h}(t) t - C_4 \bar{h}(t^*) t^2 \quad . \tag{2-13}$$

Using (2-10) in (2-13) and letting t^* approach t gives the following quadratic equation

$$(C_1 + 0.5\, C_3 t) h^2 + 0.5 C_4 t^2 h - C_2 t^2 \simeq 0 \tag{2-14}$$

which has the solution

$$h(t) \simeq \frac{-0.5 C_4 t^2 + \left[(0.5 C_4 t^2)^2 + 4(C_1 + 0.5 C_3 t) C_2 t^2\right]^{\frac{1}{2}}}{2C_1 + C_3 t} \tag{2-15}$$

Equation (2-15) expresses the height of the glass in the pipe at any time t for which (2-10) is approximately true. *

The height h_{eq} at which the glass will equilibrate at steady state occurs when

$$\frac{dh}{dt} = 0 = v \quad . \tag{2-16}$$

Using (2-16) in (2-5) gives

$$\boxed{h_{eq} = \frac{C_2}{C_4} = \frac{144P_{atm}g_o}{\rho g} + d_s} \quad . \tag{2-17}$$

(isothermal flow)

It is worthwhile to note that steady state glass flow cannot be maintained for $h \geqslant h_{eq}$ since the glass velocity goes to zero at this height. This is an important limiting factor affecting the design of an evacuated canister.

The glass velocity can be obtained by differentiating (2-15) with respect the time according to (1-2), but is more easily obtained by letting t^* approach t in (2-12) to get

$$\boxed{v(t) \simeq \frac{1}{C_1}\left[\frac{C_2 t}{h(t)} - \frac{C_3 h(t)}{2} - \frac{C_4 t}{2}\right]} \quad . \tag{2-18}$$

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* Equation (2-15) is expected to hold as long as h(t) is rising steadily. However, as $t \to \infty$, $\bar{h} \to h_{eq}$ [see (2-17)], which violates (2-10). Thus (2-15) is not accurate for $t \to \infty$ but is useful for predicting the early behavior of the flow transient.

where the value of h(t) in (2-18) is given by (2-15).

Equation (2-15) is plotted in Figure 3 for a glass velocity of 10 poise *. Note that there is a dramatic difference in the time required for the glass to reach any height greater than 1-2 feet as a function of pipe size. This difference is pronounced for pipe sizes at or below 2", but is much smaller for larger pipe sizes. If (1-3) and (1-6) are divided through by the pipe flow area πR_i^2, the result is

$$\rho \frac{d(hv)}{dt} = 144 P_{atm} g_o + \rho d_s g - \frac{8\mu hv}{R_i^2} - \rho hg \quad . \qquad (2\text{-}19)$$

The third term on the right hand side of (2-19) represents the downward acting frictional force which retards glass flow up the pipe, and is inversely proportional to R_i^2. It is this force which severely retards the flow of glass in small diameter pipes even under isothermal flow conditions. In order to suck glass up to the 8-10 ft elevation required to remove glass from a full scale DWPF melter, supplementary heating of the evacuated pipe would probably be required in order to prevent glass from solidifying in the pipe. This is an undesirable complication however, and can be eliminated by simply using a larger diameter pipe.

Figure 3 indicates that the optimum pipe size is in the range of 3-4". Larger pipe would be unacceptable because of difficulty in

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* Nominal viscosity of frit 131 - TDS3A and frit 131-high Fe glasses at 1050 - 1150°C.[3]

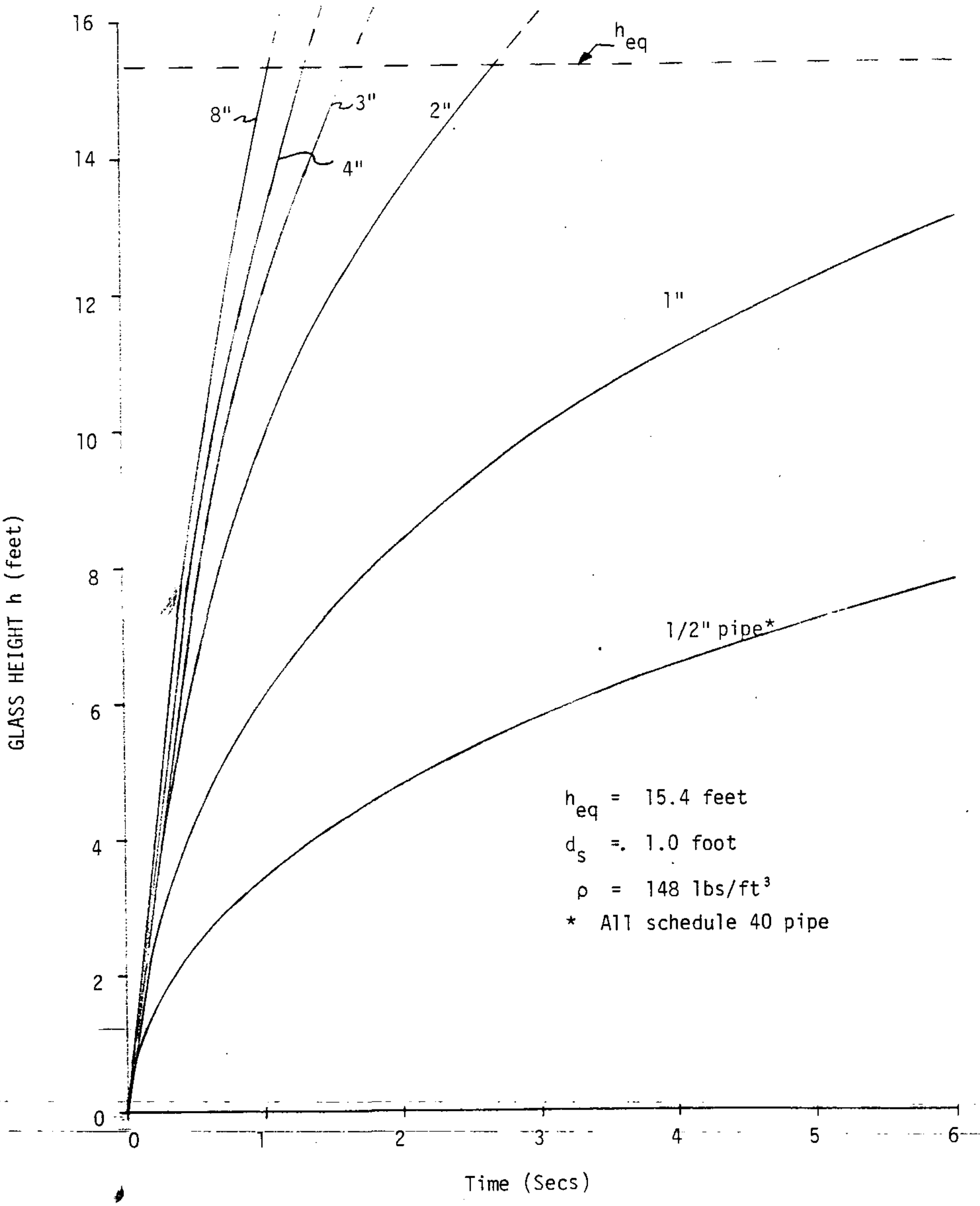

FIGURE 3 - GLASS HEIGHT VERSUS TIME AT A VISCOSITY OF 10 POISE

inserting the pipe through a port in the melter lid, and there is little improvement in performance for larger pipe anyway.

Figure 4 shows the glass velocity (2-18) as the glass rises up the suction pipe. Although not plotted,* it is worth noting that at time t = 0, the glass velocity must be zero for all the pipes. Immediately after the aluminum plug melts at the bottom of the suction pipe, there is a rapid acceleration of the glass up the pipe. Rearranging (2-19) into upward forces and downward forces gives

$$144\ P_{atm} g_o + \rho d_s g = \rho \frac{d(hv)}{dt} + \frac{8\mu h v}{R_i^{\,2}} + \rho h g \quad . \qquad (2\text{-}20)$$

upward downward

Note that the downward forces are all a function of glass height h, while the upward forces are independent of h and t. Thus for small h, rapid acceleration occurs, but this is quickly opposed by inertial, frictional, and gravitational forces, all tending to reduce the glass velocity.

For all pipes, the glass velocity drops rapidly after flow is initiated, but for larger pipes (⩾2") it drops less rapidly due to a sharp reduction in the frictional force with increasing R_i.

If the suction pipe is made large enough so that glass will reach some desired elevation very quickly, then the glass flow will essentially be isothermal without the need for supplementary heat around the suction pipe.

Figure 4 shows that for pipe sizes ⩾2", there will be a significant glass velocity even when the glass stream first reaches its equilibrium height h_{eq}. This indicates that the glass will surge past h_{eq} initially before settling down to h_{eq} at steady state with zero velocity.

* Equation (2-18) indicates that v(0) is indeterminate although h(0)= 0 by (2-15). This occurs because the momentum change in the glass pool is not included in the model and also because of the approximations made in deriving (2-18).

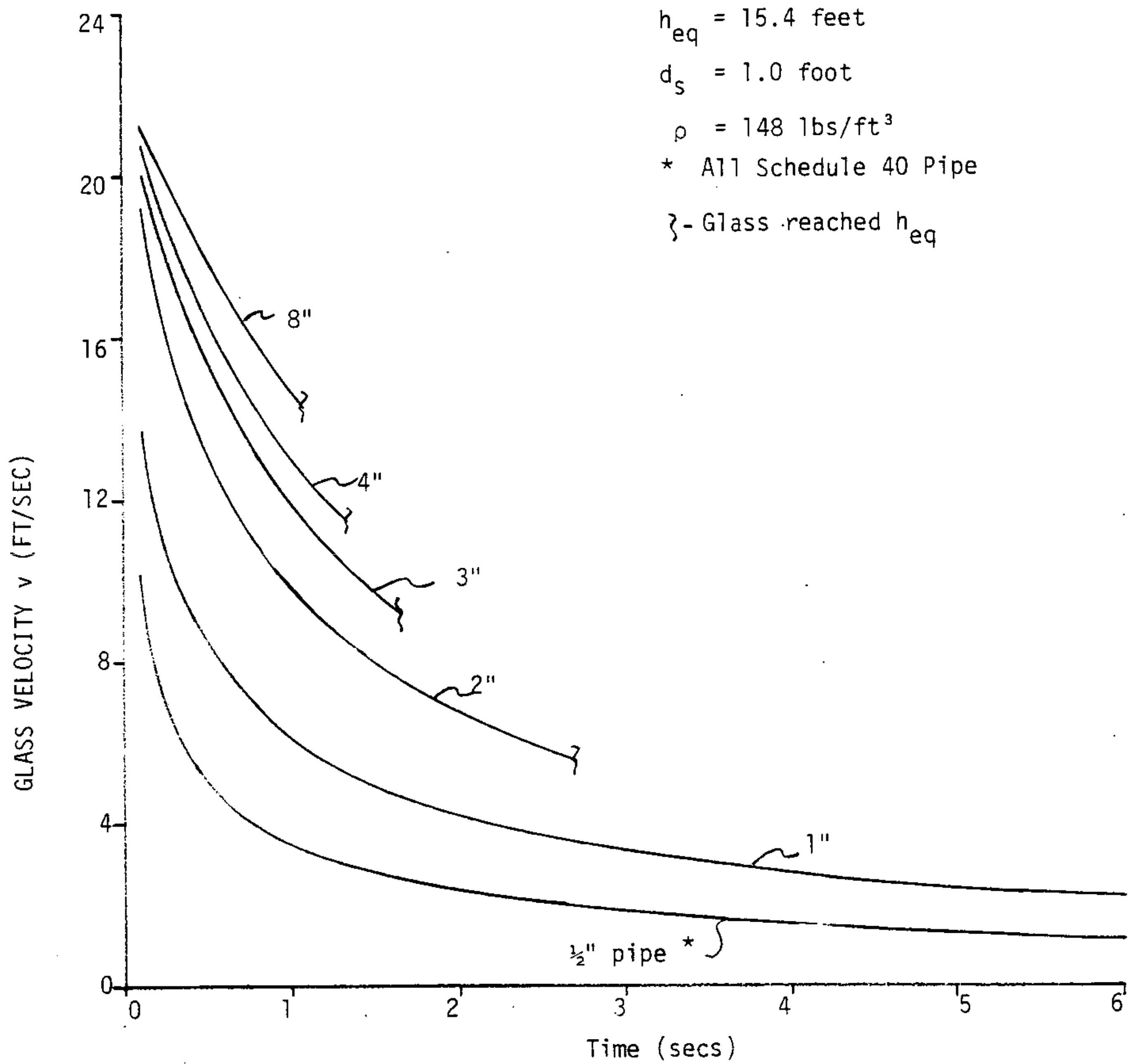

FIGURE 4 - GLASS VELOCITY VERSUS TIME AT A VISCOSITY OF 10 POISE

An initial, rapid surge of the glass stream up the suction pipe is highly desirable in order to eliminate the requirement for supplementary heating of the pipe. However, it is the steady state glass velocity* which determines whether the glass will freeze while most of the canister filling operation is occurring. Figure 4 indicates that the steady state glass velocity will be substantially less than that which occurs during the initial flow transient.

The viscosity of a frit 131/high Al glass is in the range of 50-100 poise at melter operating temperatures.[3] Glass height and velocity are plotted in Figures 5 and 6 for a glass viscosity of 100 poise. Since the frictional force (see (2-19)) is also directly proportional to the viscosity μ, note that it takes longer for a 100 poise glass to reach a given elevation in the same suction pipe compared to a 10 poise glass, especially for small diameter pipes. Again because of the inverse dependence of the frictional force on R_i^2, larger pipes are less sensitive to the effect of the frictional force.

A 3-4" pipe is still probably satisfactory for a 100 poise glass since the required 8-10 ft elevation for useful application in a DWPF melter is achieved in 2-4 seconds. However, Figure 6 shows that both the duration of the initial flow transient and the transient glass velocity are reduced for the higher viscosity glass.

The time required for the glass to rise to an arbitraty height in the pipe can be obtained by solving (2-14) for t instead of h. Rearranging gives

$$(0.5C_4h - C_2)t^2 + 0.5C_3h^2t + C_1h^2 = 0 \qquad (2\text{-}21)$$

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* To be considered in Section 3.

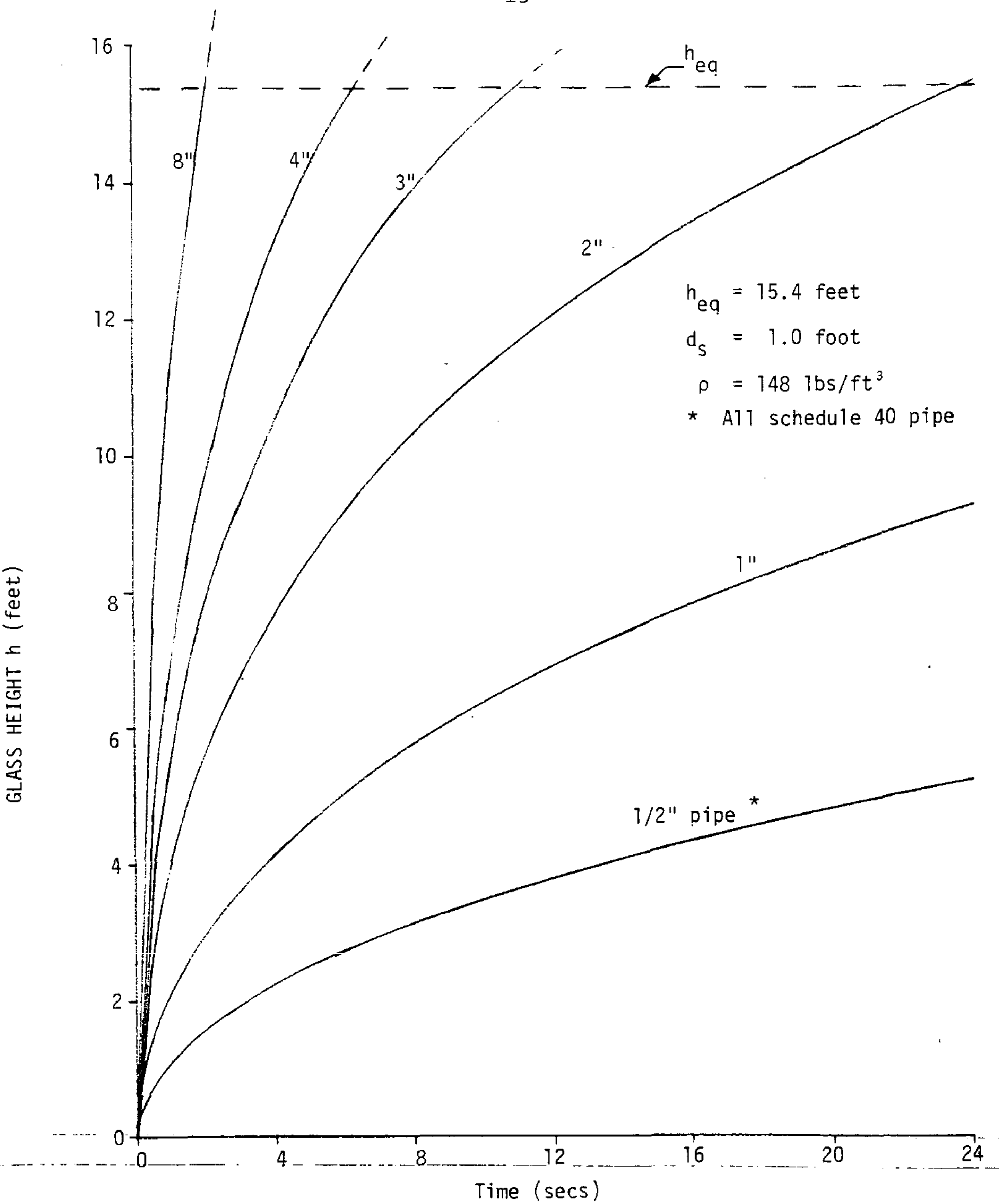

FIGURE 5 - GLASS HEIGHT VERSUS TIME AT A VISCOSITY OF 100 POISE

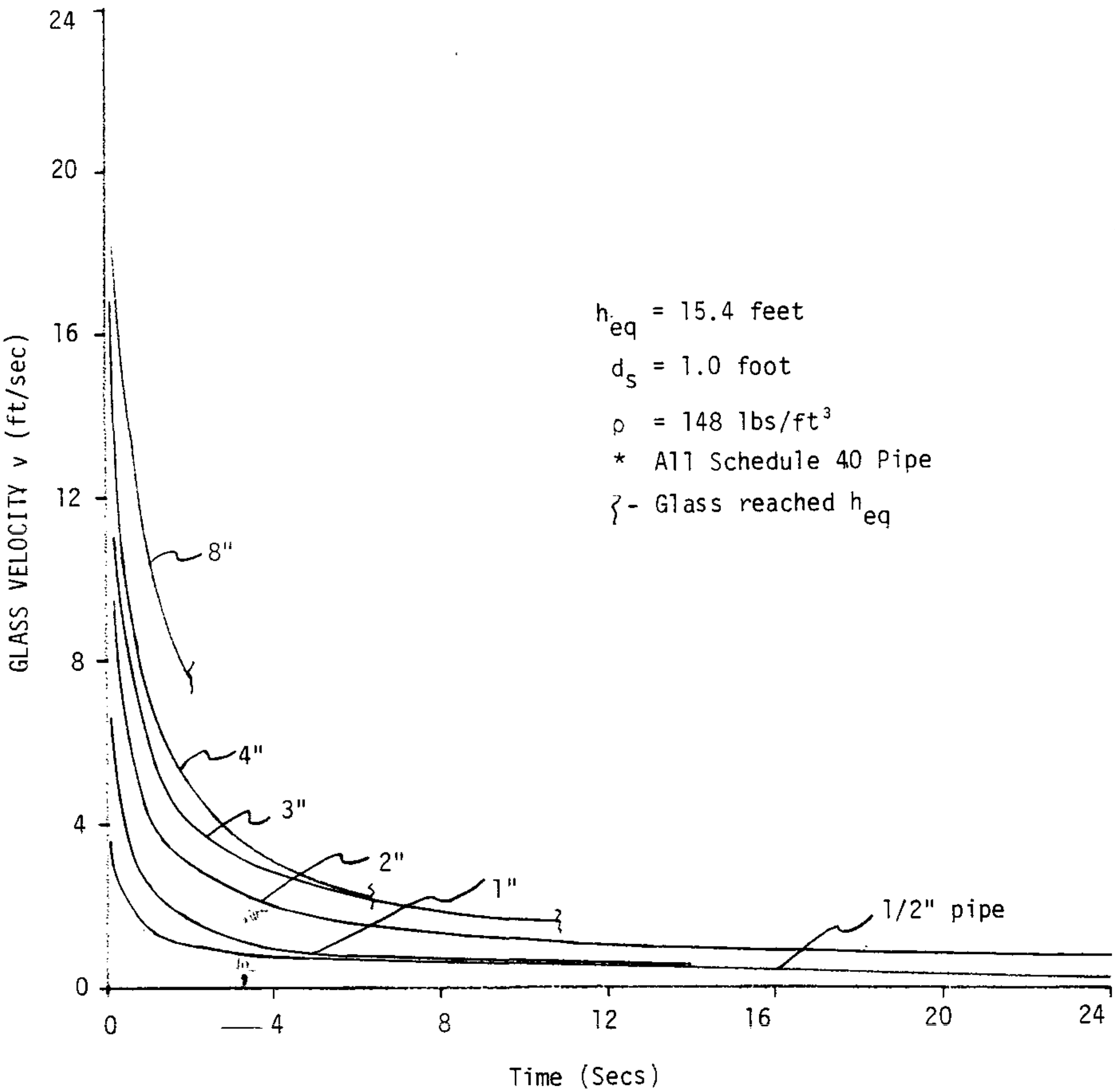

FIGURE 6 - GLASS VELOCITY VERSUS TIME AT A
VISCOSITY OF 100 POISE

which has the solution

$$t = \frac{-0.5C_3h^2 - \left[(0.5C_3h^2)^2 - 4(0.5C_4h - C_2)C_1h^2\right]^{\frac{1}{2}}}{C_4h - 2C_2} \qquad (2\text{-}22)$$

If it is desired to find the time required for the glass to rise to its equilibrium height h_{eq} during the initial flow transient, (2-17) can be substituted into (2-22) to yield

$$t(h_{eq}) = \frac{0.5C_3C_2}{C_4^2} + \frac{1}{C_2}\left\{\left[0.5C_3\left(\frac{C_2}{C_4}\right)^2\right]^2 + \frac{2C_1C_2^3}{C_4^2}\right\}^{\frac{1}{2}} \quad . \qquad (2\text{-}23)$$

Values of the rise time $t(h_{eq})$ are presented in Table 1 for standard pipe sizes. For small diameter pipe the values of $t(h_{eq})$ are large enough to allow significant cooling of the glass to occur without the presence of supplementary heating. This of course violates the assumption of isothermal flow, and should lead to a significantly longer time for the glass to reach h_{eq}. It is even possible that the glass may be cooled enough to solidify before reaching h_{eq}.

For pipe sizes in the range of 4-5" or larger, the rise time $t(h_{eq})$ is small enough that the glass should reach h_{eq} before significant cooling occurs even if supplementary heating around the pipe is not used. The assumption of isothermal flow is then justified, and the rise times $t(h_{eq})$ in Table 1 are expected to be reasonably accurate.

TABLE 1 - RISE TIME REQUIRED FOR GLASS TO FIRST REACH ITS FINAL EQUILIBRIUM HEIGHT h_{eq}

Nominal Pipe Size ▲	Inside Radius (Inches)	$t(h_{eq})^{*}$ (secs)	$t(h_{eq})^{\dagger}$ (secs)
1/8	0.135	138	1378
1/4	0.182	75.8	758
1/2	0.273	33.7	337
1	0.525	9.22	91.9
2	1.034	2.70	23.5
3	1.534	1.65	10.8
4	2.013	1.34	6.35
5	2.524	1.20	4.17
6	3.032	1.13	3.05
8	3.991	1.06	2.05
10	5.010	1.03	1.60

▲ Schedule 40 pipe.

* μ = 10 poise, ρ = 148 lb_m/ft^3, d_s = 1.0 ft.

† μ = 100 poise, ρ = 148 lb_m/ft^3, d_s = 1.0 ft.

For a typical DWPF glass, the second term under the radical in (2-23) becomes dominant for large values of R_i. This leads to

$$t(h_{eq}) \simeq \left[\frac{2C_1C_2}{C_4^2}\right]^{\frac{1}{2}} \quad . \qquad (R_i \text{ large}) \tag{2-24}$$

Inserting the values of the constants gives

$$t(h_{eq}) \simeq \left\{\frac{2(144P_{atm}g_o + \rho d_s g)}{\rho g^2}\right\}^{\frac{1}{2}} \qquad (R_i \text{ large}) \tag{2-25}$$

or

$$\boxed{t(h_{eq}) \simeq 0.98 \text{ secs}} \quad . \qquad (R_i \text{ large}) \tag{2-26}$$

From inspection of Table 1, it is evident that (2-26) is reasonably accurate for nominal pipe sizes ≥5" at a glass viscosity of 10 poise. At a viscosity of 100 poise, it is reasonably accurate for pipe sizes >10".

Inspection of (2-23) shows that (2-24) also results for the idealized case of frictionless flow ($C_3 = 0$). Thus (2-26) is the minimum time required for the glass to reach h_{eq} and will always be exceeded for real pipes with friction. Low viscosity glass can approach this minimum time quite closely in moderately sized pipes, while high viscosity glass requires a much larger pipe (Figure 7).

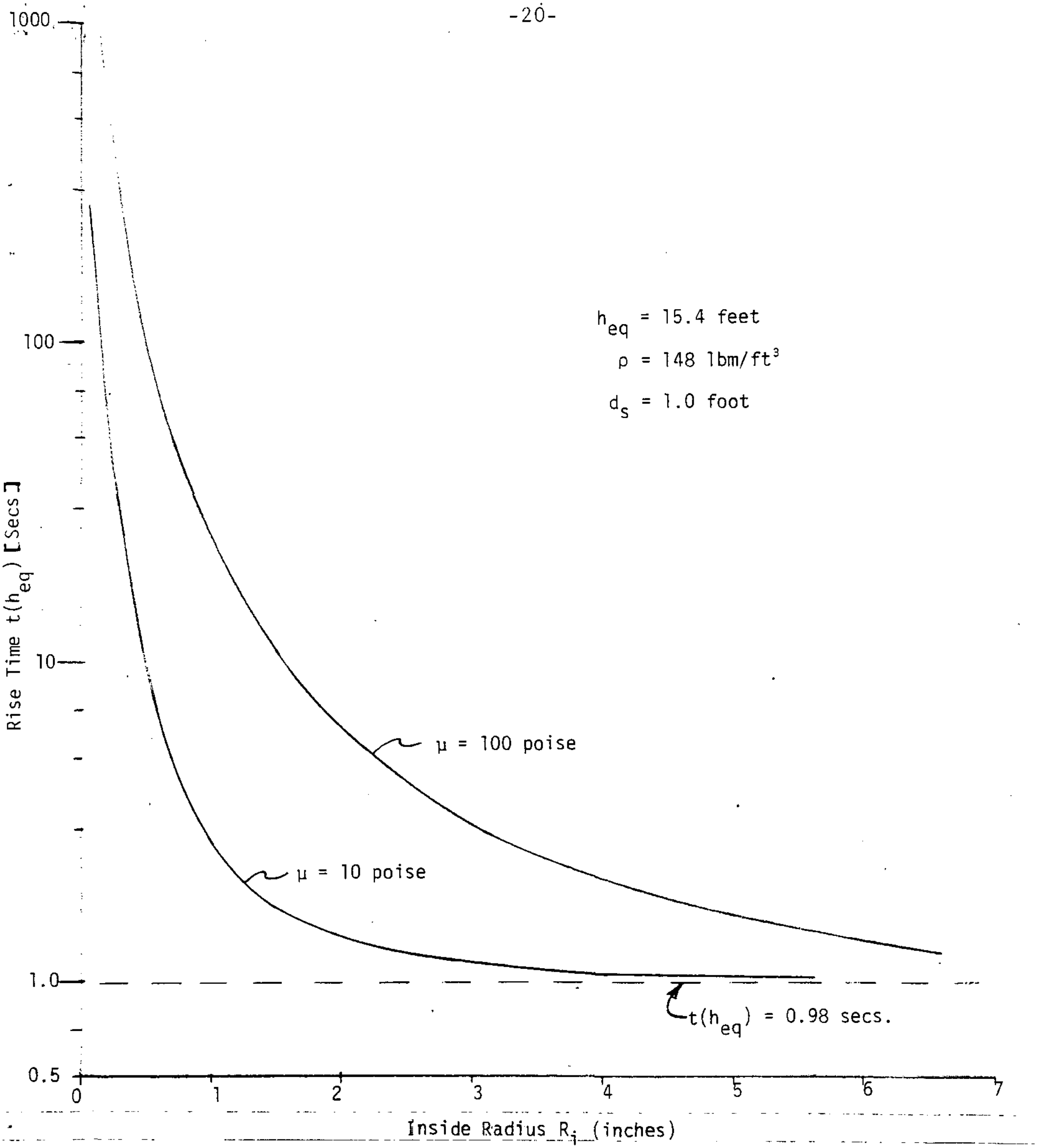

FIGURE - 7 TIME REQUIRED FOR GLASS TO RISE TO h_{eq} VERSUS VISCOSITY AND INSIDE RADIUS OF THE PIPE

3. Steady State, Isothermal Flow

After the transient effects of the initial glass surge have died away (a few seconds), one must rely upon the steady state glass velocity in order to fill the remainder of the glass canister. Improper design can lead to premature solidification of the glass before the canister is filled, even though flow may have been successfully initiated up the suction pipe. This can occur because the steady state glass velocity will in general be much lower than that of the initial flow transient. If heat losses from the pipe are excessive, premature solidification of the glass is inevitable.

Isothermal flow conditions will again be assumed for purposes of computing the glass velocity. Heat transfer requirements will then be developed which ensure that the isothermal flow condition is approximately satisfied.

At steady state, the suction pipe is assumed to be full and discharging glass into the evacuated canister (Figure 8). The mass and momentum balances developed in Section 1 reduce to a simple force balance of the form

$$144P_{atm}\pi R_i^2 g_o + \rho\pi R_i^2 d_s g = 8\pi\mu(T_o)L_e v_{ss} + \rho\pi R_i^2 \Delta h\ g \qquad (3\text{-}1)$$

where

L_e = equivalent length* of the pipe from the suction end to the discharge point inside the canister (ft),

Δh = elevation of the discharge end of the suction pipe minus the elevation of the suction end (ft),

v_{ss} = steady state glass velocity (ft/sec).

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* The equivalent length takes into account the additional pressure drop caused by bends in the piping.[4]

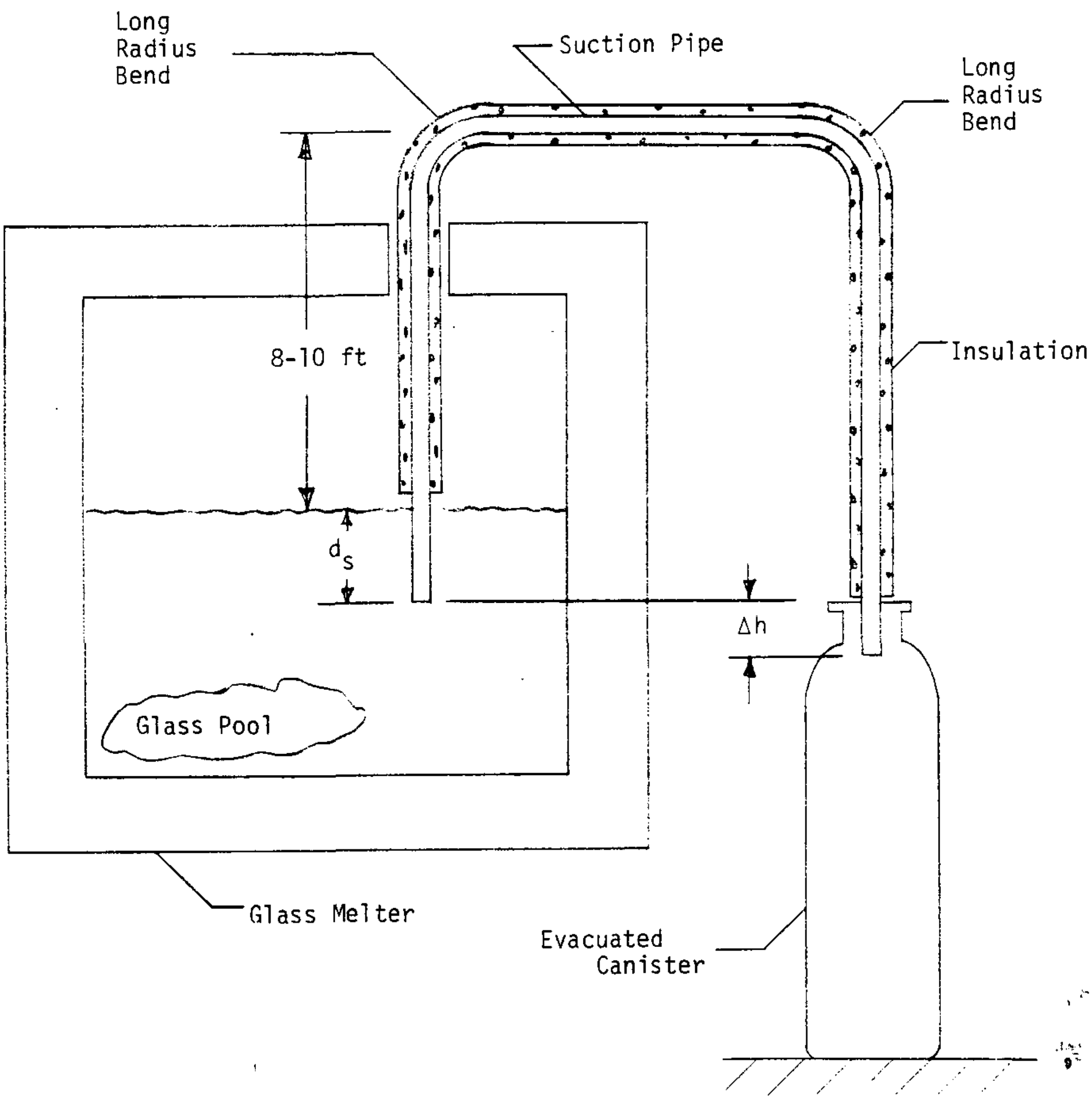

FIGURE 8 - TYPICAL EVACUATED CANISTER FOR A DWPF MELTER

Solving (3-1) for v_{ss} gives

$$v_{ss} = \frac{R_i^2}{8\mu(T_o)L_e}\left\{144P_{atm}g_o + \rho g(d_s - \Delta h)\right\} \quad (3\text{-}2)$$

In order to make the glass flow isothermal (or nearly so), it is desirable to make v_{ss} as large as practical. Inspection of (3-2) gives four clear design objectives:

(1) Make the discharge end of the suction pipe as low as possible in order to maximize $(d_s - \Delta h)$. If the discharge end of the suction pipe is below the suction end ($\Delta h < 0$), then the net gravitational force will increase v_{ss} instead of retard it, resulting in a siphoning effect. Also note that if one selects $\Delta h \geq h_{eq}$, then $v_{ss} \leq 0$. This means that after the initial flow surge up into the suction pipe, the glass flow will either reverse or stop at isothermal steady state conditions. Practically speaking, this means that the technique will fail either by draining the glass in the suction pipe back into the glass pool or that glass solidification will occur in the suction pipe.

(2) Make the equivalent length L_e of the suction pipe as short as possible.

(3) Make sure the glass pool is as hot as is permissible before initiating flow. This will lower the viscosity $\mu(T_o)$.

(4) Make the radius of the suction pipe R_i as large as practical. Having optimized the first three criteria, this criterion can be used to remarkably improve v_{ss} since v_{ss} is directly proportional to the square of R_i.

Figure 9 shows the steady state glass velocity in the suction pipe as a function of the inside radius of the pipe. The discharge elevation of the suction pipe has been arbitrarily selected to match the elevation of the glass pool surface so that $(d_s - \Delta h)$ is zero in (3-2). This will be roughly true for the DWPF melter if the evacuated canister is allowed to sit on the melt cell floor as it is being filled. The value of $L_e = 48$ ft used is a nominal value for a DWPF evacuated canister with two 90^0 bends (not standard elbows) in the suction pipe (Figure 8). Note that the glass velocities are low, especially for a high viscosity glass.

The mass flow rate of glass in the suction pipe is simply

$$f = \rho \pi R_i^{\,2} v \qquad (3\text{-}3)$$

where f is in lbs_m/sec.

Using (3-2) in (3-3) gives the steady state mass flow rate into the canister as

$$\boxed{f_{ss} = \frac{\rho \pi R_i^{\,4}}{8\mu(T_o) L_e} \left\{ 144 P_{atm} g_o + \rho g (d_s - \Delta h) \right\}} \qquad (3\text{-}4)$$

Note the dependence of f_{ss} on the fourth power of R_i.

Values of f_{ss} are plotted in Figure 10, and may be used to estimate the time required to fill a standard DWPF canister. Using a 3" schedule 40 suction pipe, and the nominal parameters given in Figure 10, the time required to suck 3420 lbs* into a standard canister varies from 1.9 minutes for a 10 poise glass to 19 minutes for a 100 poise glass.

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* Reference amount of glass per canister according to J. W. Kelker, Jr.

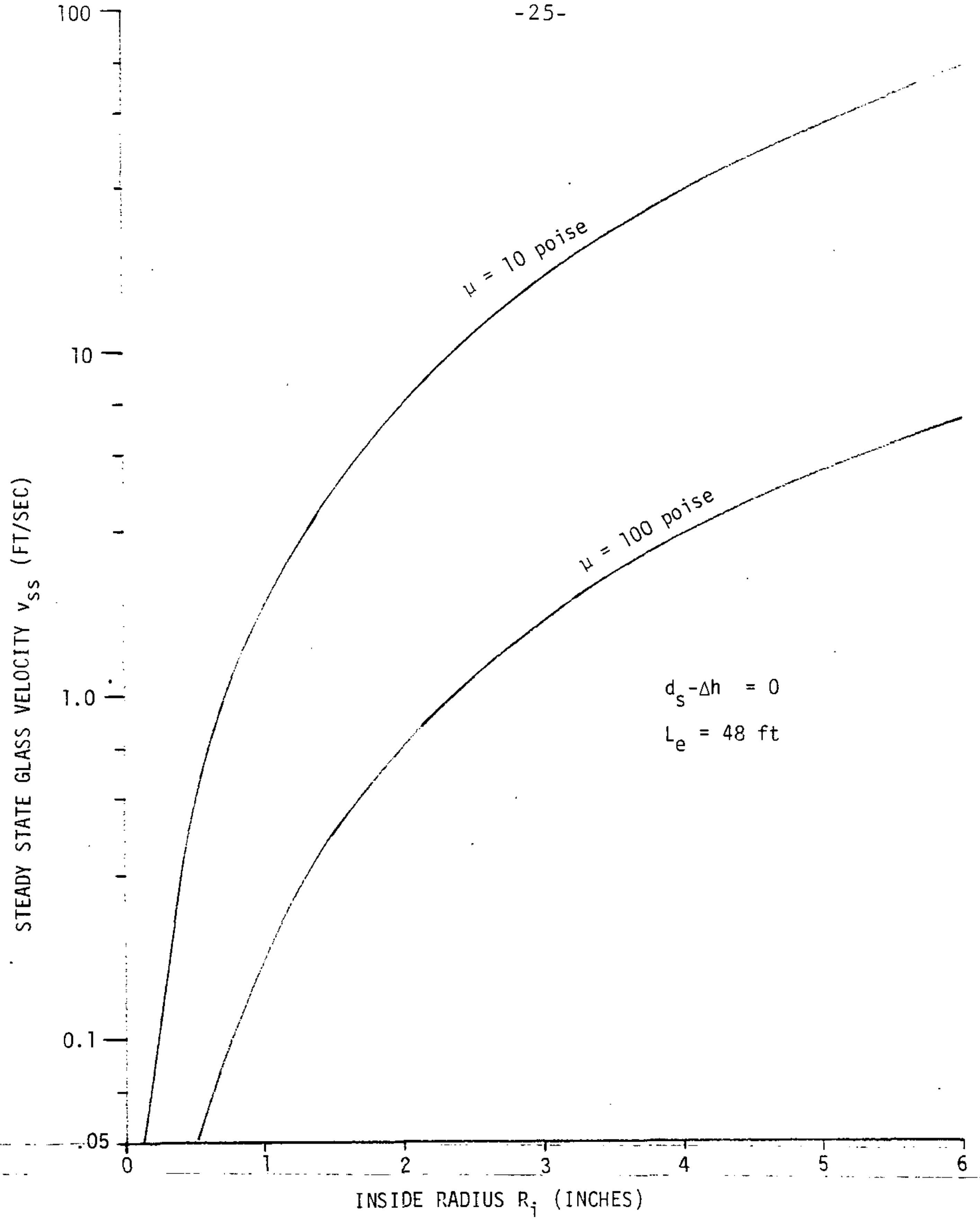

FIGURE 9 - STEADY STATE GLASS VELOCITY VERSUS INSIDE RADIUS OF THE PIPE

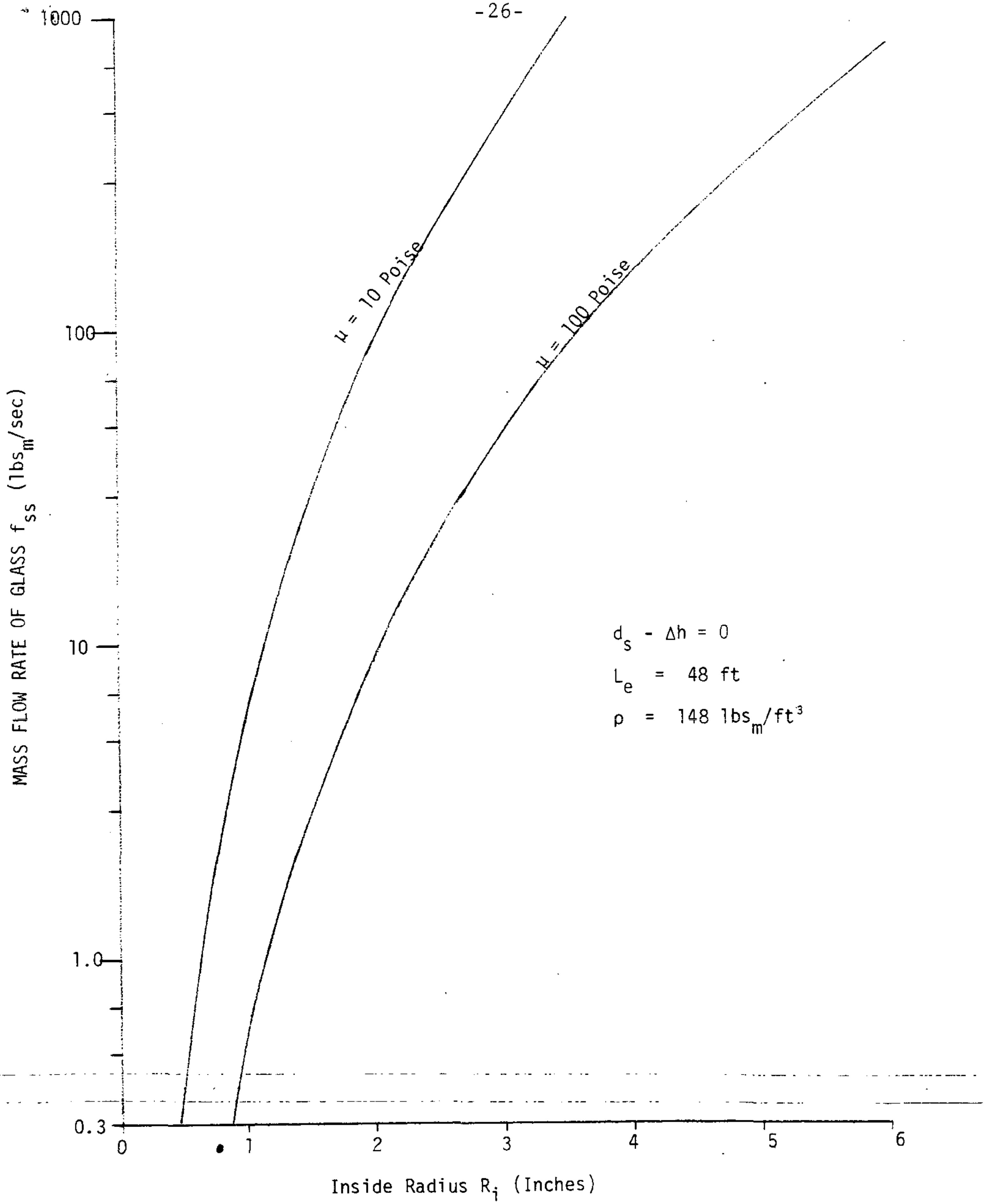

FIGURE 10 - STEADY STATE GLASS FLOW INTO A TYPICAL DWPF EVACUATED CANISTER

4. Achieving Steady State, Isothermal Flow

True isothermal flow in the suction pipe is of course, not possible unless supplementary heating is provided in or around the pipe such that the pipe is held at T_o, i.e., the temperature at which the glass enters the submerged end. This is an undesirable complication however, and it is preferable to settle for roughly isothermal flow if it can be achieved in a simple manner.

Using Figure 11, conservation of energy at steady state in the suction pipe requires that

$$0 = \text{Energy In} - \text{Energy Out} \tag{4-1}$$

or

$$0 \simeq \rho\pi R_i^{\,2} v c_p \left[T_g(z) - T_g(z + \Delta z)\right] - h_{gp} 2\pi R_i \Delta z \left[T_g(z) - T_p(z)\right] \tag{4-2}$$

where

c_p = mean specific heat of the glass from $T_g(z)$ to $T_g(z + \Delta z)$ [Btu/lb$_m$- ^{0}R],

$T_g(z)$ = glass temperature at position z [^{0}R],

h_{gp} = heat transfer coefficient from the glass to the inside wall of the pipe [Btu/hr-ft^2-^{0}R],

Δz = arbitrary element of length along the suction pipe [ft],

$T_p(z)$ = inside wall temperature of the pipe at z [^{0}R],

and the other symbols are as previously defined.

Dividing (4-2) by $\pi R_i \Delta z$ and taking $\lim_{\Delta z \to o}$ gives

$$\rho R_i v c_p \frac{dT_g}{dz} = -2h_{gp}(T_g - T_p) \quad . \tag{4-3}$$

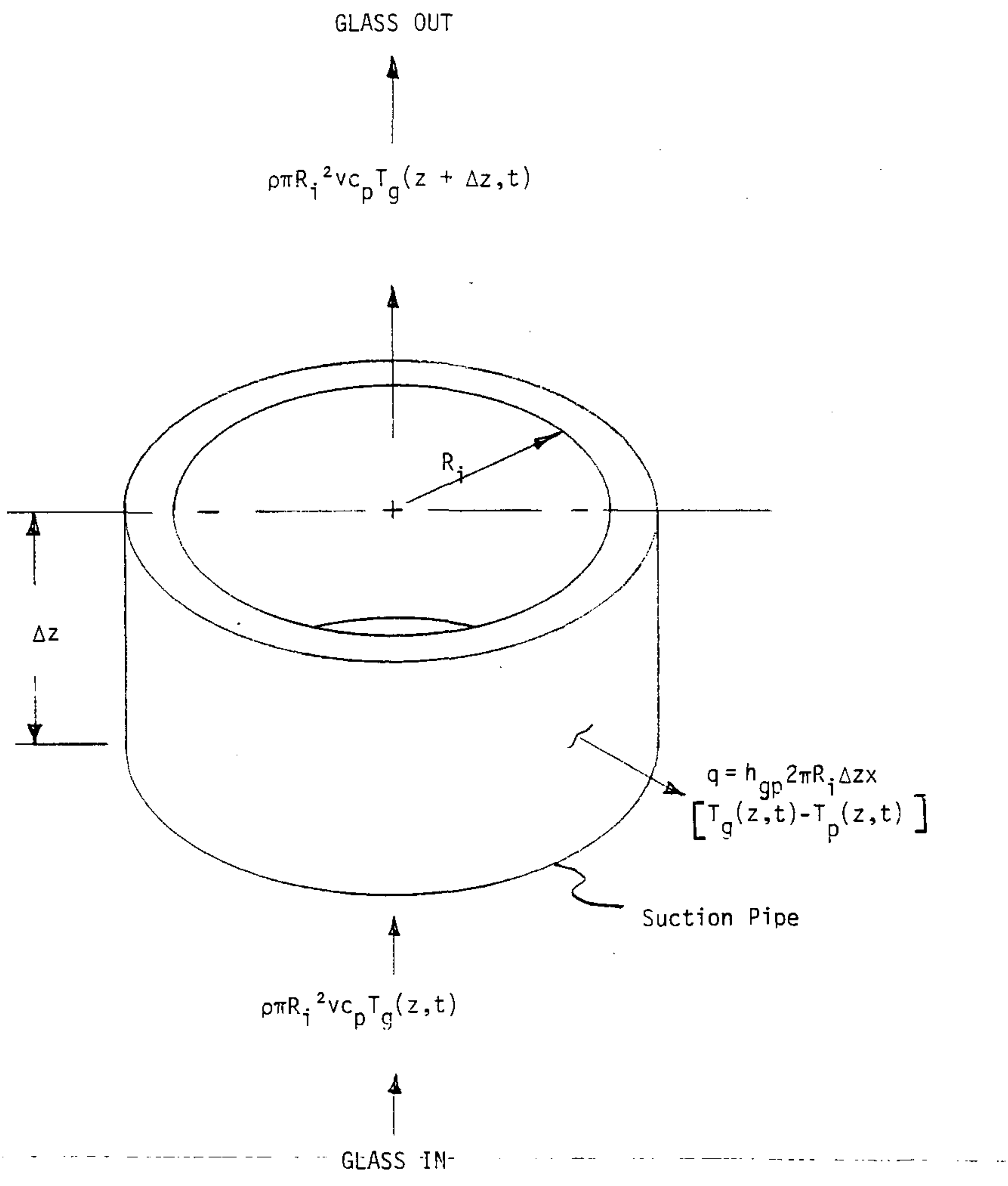

FIGURE 11 - VOLUME ELEMENT FOR ENERGY BALANCE ON GLASS IN THE TUBE

If the pipe is insulated in some fashion, then conservation of energy at the inside of the pipe wall requires

$$2\pi R_i \Delta z h_{gp} \left[T_g(z) - T_p(z) \right] = 2\pi R_i \Delta z U_{oa} \left[T_p(z) - T_{amb} \right] \qquad (4\text{-}4)$$

where

U_{oa} = overall heat transfer coefficient for conduction through the pipe wall and insulation plus natural convection and radiation to the surroundings * [Btu/hr-ft^2-^{0}R],

T_{amb} = ambient temperature[^{0}R].

Equation (4-4) reduces to

$$h_{gp}(T_g - T_p) = U_{oa}(T_p - T_{amb}) \quad , \qquad (4\text{-}5)$$

or

$$T_p = \frac{h_{gp} T_g + U_{oa} T_{amb}}{h_{gp} + U_{oa}} \quad . \qquad (4\text{-}6)$$

The limiting value of the Nusselt number Nu for laminar flow is[5]

$$Nu = \frac{h_{gp} R_i}{k_g} \approx 4.0 \qquad (4\text{-}7)$$

where k_g = thermal conductivity of the glass [Btu/hr-ft-^{0}R] .

Thus

$$h_{gp} \approx \frac{4k_g}{R_i} \quad . \qquad (4\text{-}8)$$

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* Based on inside heat transfer area of suction pipe.

If one requires that the pipe be well insulated, then

$$U_{oa} << h_{gp} \simeq \frac{4k_g}{R_i} \qquad (4\text{-}9)$$

which is easily satisfied in practice. Then (4-6) becomes

$$T_p \simeq T_g + \frac{U_{oa}\ T_{amb}}{h_{gp}} \quad . \qquad (4\text{-}10)$$

Substituting (4-10) in (4-3) gives

$$\rho R_i v c_p \frac{dT_g}{d_z} \simeq 2\ U_{oa}\ T_{amb} \quad . \qquad (4\text{-}11)$$

Integrating (4-11) over the insulated length L_i of the suction pipe gives

$$\Delta T_{gi} \simeq \frac{2U_{oa}T_{amb}L_i}{\rho R_i v c_p} \qquad (4\text{-}12)$$

where

ΔT_{gi} = temperature drop of the glass across the insulated portion of the pipe [°R]

Using (3-2) in (4-12) gives

$$\Delta T_{gi} \simeq \frac{16U_{oa}T_{amb}L_i\mu(T_o)L_e}{\rho R_i{}^3 c_p \left\{144P_{atm}g_o + \rho g(d_s-\Delta h)\right\}} \qquad (4\text{-}13)$$

which gives the approximate temperature drop of the glass as it passes through an insulated length L_i of the suction pipe.

In general the same design objectives that were set forth in Section 3 for achieving a large steady state glass velocity v_{ss} are also applicable for minimizing ΔT_{gi} in (4-13). Note especially however, that ΔT_{gi} varies inversely as the cube of R_i, indicating that the chance of premature solidification of the glass in the suction pipe can be sharply reduced by simply increasing the pipe radius.

Equation (4-12) is plotted in Figures 12 and 13 for different heat transfer coefficients using $v = v_{ss}$ from (3-2). The assumption of isothermal flow is satisfied with $R_i > 0.5$ inches for a 10 poise glass and with $R_i > 1.0$ inch for a 100 poise glass. No difficulty is anticipated in maintaining steady state flow through the suction pipe in spite of the relatively low glass velocity if the pipe is insulated to obtain the indicated overall heat transfer coefficients. Values of U_{oa} are given in Table 2, and indicate that only a moderate amount of insulation is required to achieve the desired condition of isothermal flow.

TABLE 2 - OVERALL HEAT TRANSFER COEFFICIENT FOR VARIOUS PIPE SIZES

Pipe Size	U_{oa} $\left[Btu/hr\text{-}ft^2\text{-}^0R\right]^\dagger$
1/4"	3.5
1	2.0
2	1.6
3	1.3
4	1.2

† Based on inside pipe radius with a 1" thick layer of Kaowool blanket wrapped around the suction pipe.

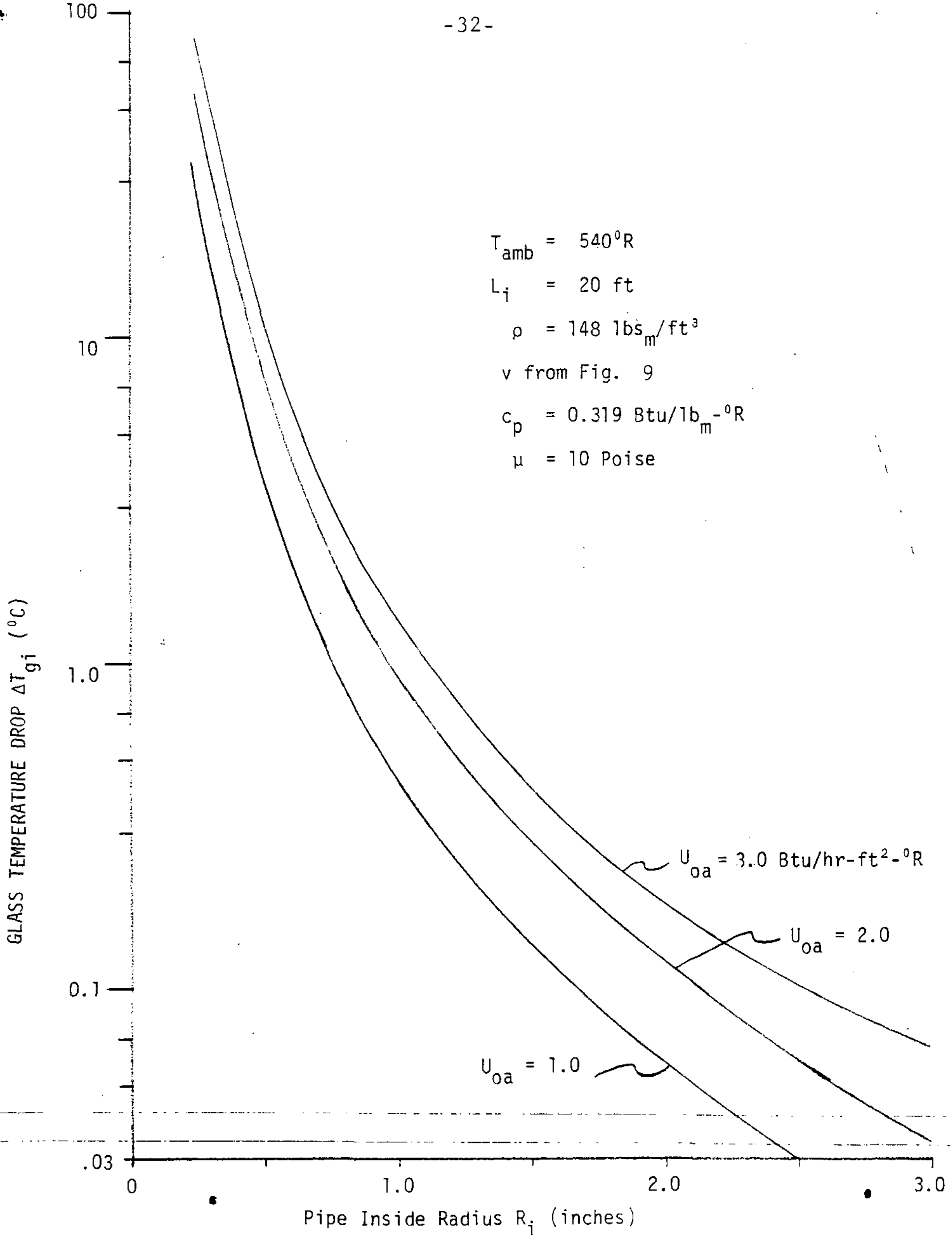

FIGURE 12 - STEADY STATE GLASS TEMPERATURE DROP IN A SUCTION PIPE FOR A TYPICAL EVACUATED CANISTER WITH A 10 POISE GLASS

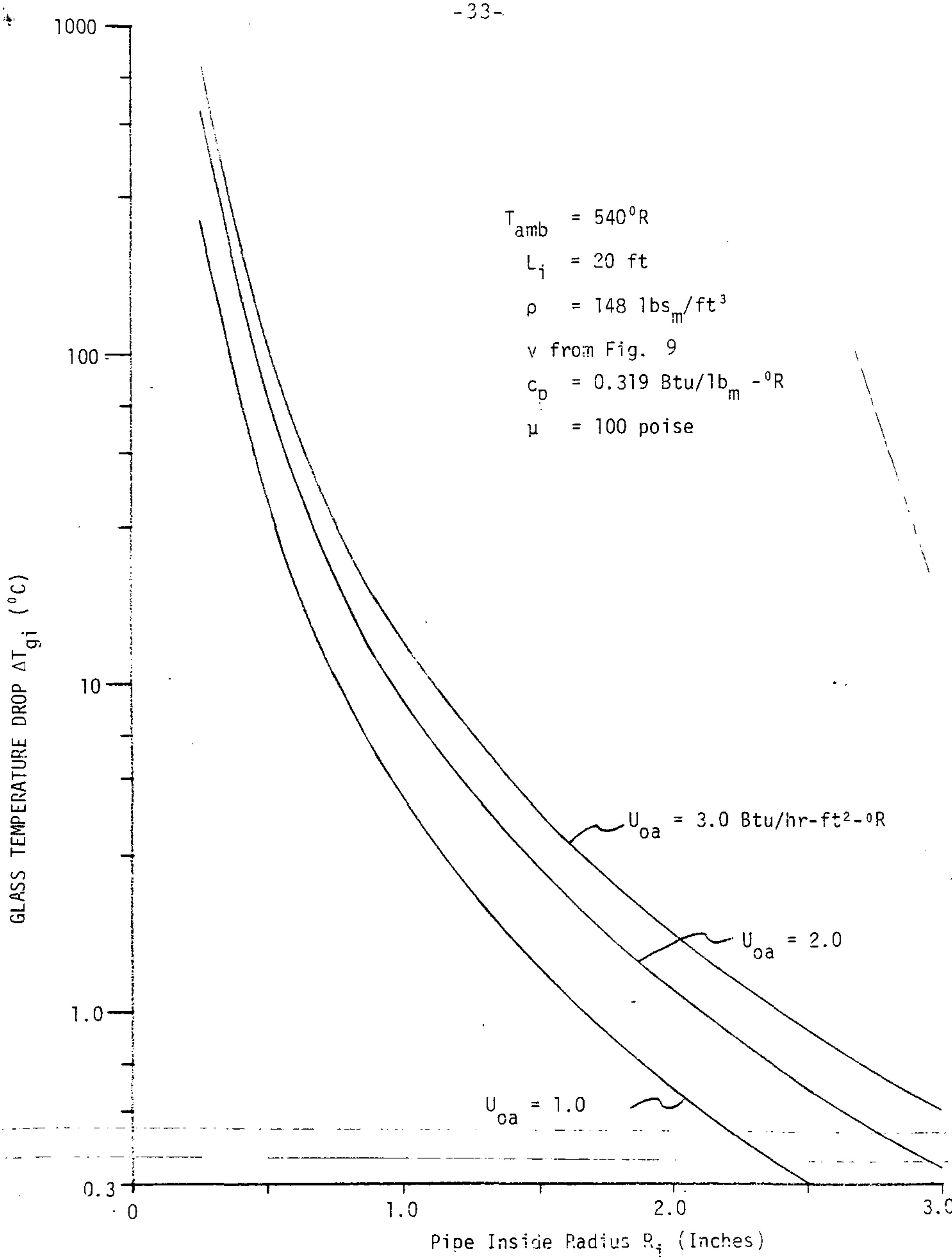

FIGURE 13 - STEADY STATE GLASS TEMPERATURE DROP IN A SUCTION PIPE FOR A ~~TYPICAL DWPF EVACUATED CANISTER WITH A 100 POISE GLASS~~

5. Summary of Glass Flow Behavior For An Evacuated Canister

Following melting of the fusible plug at the submerged end of the suction pipe, there is an initial surge of glass up the pipe. In small pipes this surge is primarily limited by frictional forces, and not gravitational or inertial forces. The frictional force is proportional to the glass viscosity μ and inversely proportional to the square of the pipe radius R_i. This surge must be of sufficient volume and rapidity so that energy losses from the glass to the suction pipe do not significantly cool the glass. The glass velocity dies off rapidly after the initial surge to a much lower steady state value v_{ss} which must be relied upon for filling most of the evacuated canister. Moderate insulation around the suction pipe will ensure that steady state glass flow into the canister is approximately isothermal.

6. Summary of Design and Operating Recommendations for An Evacuated Canister

The following recommendations are directed toward removal of glass from a full-scale DWPF melter by use of an evacuated canister. It is assumed that the glass viscosity is in the range of 10-100 poise, and that the maximum required lifting height from the glass surface to the first bend in the suction pipe (Figure 8) is 8-10 feet.

- The minimum recommended size of the suction pipe is 3" pipe. Smaller diameter pipe is not recommended since premature glass solidification may occur unless supplementary heating of the pipe is provided.
- The canister and suction pipe should be evacuated to the lowest practical absolute pressure before inserting the suction pipe into the melt pool.
- A slight advantage is gained by inserting the suction pipe as deeply as practical into the melt pool. This increases d_s and hence the upward force that accelerates the initial glass surge.

- The lifting height from the glass surface to the first bend in the suction pipe should be minimized (Figure 8). This will reduce the amount of heat lost by the initial glass surge and also increase the steady state glass velocity going into the canister.
- The glass pool should be as hot as is permissible before flow up the suction pipe begins. This will lower the glass viscosity and hence the frictional force which retards glass flow.
- The discharge end of the suction pipe should be as low as possible, and preferably below the suction end. This will cause the net effect of gravity to increase the steady state glass velocity v_{ss}.
- The equivalent length of the suction pipe should be as short as possible. Standard pipe elbows in the suction pipe are not recommended. A pipe <u>bend</u> of radius R_b for a pipe inside radius of R_i will give a minimum equivalent length for $4 \leq R_b/R_i \leq 6$. This will aid in increasing the steady state glass velocity v_{ss}.
- The suction pipe should be insulated along its full length except for the submerged portion in the melt pool. This includes that portion of the suction pipe in the melter plenum. A 1" thick wrap of Kaowool blanket around the suction pipe should be adequate to maintain isothermal flow under steady state conditions.
- The amount of glass sucked into the evacuated canister can be controlled by selection of the initial submerged depth d_s of the suction pipe in the glass pool. When the glass level in the melt pool drops below this end of the pipe, the vacuum will be lost and the flow will stop. This is a convenient way to terminate glass flow into the canister.

- Structural integrity of the evacuated canister and suction pipe must be properly considered. Heat losses to the suction pipe can be reduced during the initial glass surge if thin wall pipe is used. However, the structural strength of most metals is drastically reduced at the high operating temperature experienced by the suction pipe and canister. Inadequate design and construction of the evacuated canister may result in implosion during rapid filling. If personnel are to be in the test area, a secondary canister thermally insulated from the evacuated canister may be prudent.
- Successful operation of an evacuated canister will in general be more difficult with high viscosity glasses. This can be alleviated to some degree by using a suction pipe with a larger inside radius. It is extremely doubtful however, that an evacuated canister can be used to remove appreciable slag from a melter bottom.

KRR:dhw

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